

The Origin of Matter and Structure in the Universe

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Cosmology is nowadays one of the most active areas of research in fundamental science. We are going through a true revolution in the observations that are capable of providing crucial information about the origin and evolution of the universe. In the first years of the next millenium we will have, for the first time in the history of such an ancient science as cosmology, a precise knowledge about a handful of parameters that determine our Standard Cosmological Model. This standard model is based on the inflationary paradigm, a period of exponential expansion in the early universe responsible for the large scale homogeneity and flatness of our observable patch of the universe. A spectrum of density perturbations, seen in the microwave background as temperature anisotropies, could have been produced during inflation from quantum fluctuations that were stretched to cosmological size by the expansion, and later gave rise, via gravitational collapse, to the observed large scale structure of clusters and superclusters of galaxies. Furthermore, the same theory predicts that all the matter and radiation in the universe today originated at the end of inflation from an explosive production of particles that could also have been the origin of the present baryon asymmetry, before the universe reached thermal equilibrium at a very large temperature. From there on, the universe cooled down as it expanded, in the way described by the standard hot big bang model. With the observations that will soon become available in the next millenium, we will be able to test the validity of the inflationary paradigm, and determine with unprecedented accuracy the parameters of a truly Standard Model of Cosmology.

Keywords: early universe; inflation; cosmic microwave background;
cosmological parameters; large scale structure; gravitational waves;
baryogenesis; dark matter

1. Introduction

Our present understanding of the universe is based upon the successful hot big bang theory, which explains its evolution from the first fraction of a second to our present age, around 13 billion years later. This theory rests upon four strong pillars, a theoretical framework based on general relativity, as put forward by Albert Einstein and Alexander A. Friedmann in the 1920s, and three strong observational facts. First, the expansion of the universe, discovered by Edwin P. Hubble in the 1930s, as a recession of galaxies at a speed proportional to their distance to us. Second, the relative abundance of light elements, explained by George Gamow in the 1940s, mainly that of helium, deuterium and lithium [See Fig. 1], which were

cooked from the nuclear reactions that took place at around a second to a few minutes after the big bang, when the universe was a hundred times hotter than the core of the sun. Third, the cosmic microwave background (CMB), the afterglow of the big bang, discovered in 1965 by Arno A. Penzias and Robert W. Wilson as a very isotropic blackbody radiation at a temperature of about 3 degrees Kelvin (degrees Centigrade above absolute zero), emitted when the universe was cold enough to form neutral atoms, and photons decoupled from matter, approximately 300 000 years after the big bang. Today, these observations are confirmed to within a few percent accuracy, and have helped establish the hot big bang as the preferred model of the universe.

The big bang theory could not explain, however, the origin of matter and structure in the universe; that is, the origin of the matter-antimatter asymmetry, without which the universe today would be filled by a uniform radiation continuously expanding and cooling, with no traces of matter, and thus without the possibility to form gravitationally bound systems like galaxies, stars and planets that could sustain life. Moreover, the standard big bang theory assumes but cannot explain the origin of the extraordinary smoothness and flatness of the universe on the very large scales, seen by the microwave background probes and the largest galaxy catalogs [See Fig. 2]. It cannot explain the origin of the primordial density perturbations that gave rise to cosmic structures like galaxies, clusters and superclusters, via gravitational collapse; neither the quantity and nature of the dark matter that we believe holds the universe together; nor the origin of the big bang itself.

In the 1980s a new paradigm, deeply rooted in fundamental physics, was put forward by Alan H. Guth, Andrei D. Linde and others, to address these fundamental questions. According to the inflationary paradigm, the early universe went through a period of exponential expansion, driven by the approximately constant energy density of a scalar field called the inflaton. In modern physics, elementary particles are represented by quantum fields, which resemble the familiar electric, magnetic and gravitational fields. A field is simply a function of space and time whose quantum oscillations are interpreted as particles. For instance, the photon is the particle associated with the electromagnetic field. In our case, the inflaton field has associated with it a large potential energy density, which drives the exponential expansion during inflation [See Fig. 3]. We know from general relativity that the density of matter determines the expansion of the universe, but a constant energy density acts in a very peculiar way: as a repulsive force that makes any two points in space separate at exponentially large speeds. (This does not violate the laws of causality because there is no information carried along in the expansion, it is simply the stretching of spacetime.)

This superluminal expansion is capable of explaining the large scale homogeneity of our observable universe and, in particular, why the microwave background looks so isotropic: regions separated today by more than a degree in the sky were, in fact, in causal contact before inflation, but were stretched to cosmological distances by the expansion [See Fig. 4]. Any inhomogeneities present before the tremendous expansion would be washed out. Moreover, in the usual big bang scenario a flat universe, one in which the gravitational attraction of matter is exactly balanced by the cosmic expansion, is unstable under perturbations: a small deviation from flatness is amplified and soon produces either an empty universe or a collapsed one. For the universe to be nearly flat today, it must have been extremely flat at nucleosynthesis

for example, deviations not exceeding more than one part in 10^{15} . This extreme fine tuning of initial conditions was also solved by the inflationary paradigm [See Fig. 5]. Thus inflation is an extremely elegant hypothesis that explains how a region much, much greater than our own observable universe could have become smooth and flat without recourse to *ad hoc* initial conditions.

2. The origin of structure in the universe

If cosmological inflation made the universe so extremely flat and homogeneous, where did the galaxies and clusters of galaxies come from? One of the most astonishing predictions of inflation, one that was not even expected, is that quantum fluctuations of the inflaton field are stretched by the exponential expansion and generate large scale perturbations in the metric. Inflaton fluctuations are small wave-packets of energy that, according to general relativity, modify the spacetime fabric, creating a whole spectrum of curvature perturbations. The use of the word spectrum here is closely related to the case of light waves propagating in a medium: a spectrum characterises the amplitude of each given wavelength. In the case of inflation, the inflaton fluctuations induce waves in the spacetime metric that can be decomposed into different wavelengths, all with approximately the same amplitude, that is, corresponding to a scale-invariant spectrum. These patterns of perturbations in the metric are like fingerprints that characterise unequivocally a period of inflation. When matter fell in the troughs of these waves, it created density perturbations that collapsed gravitationally to form galaxies, clusters and superclusters of galaxies, with a spectrum that is also scale-invariant. Such a type of spectrum was proposed in the early 1970s (before inflation) by Edward R. Harrison, and independently by the Russian cosmologist Yakov B. Zel'dovich, to explain the distribution of galaxies and clusters of galaxies on very large scales in our observable universe.

Various telescopes, like the Hubble Space Telescope, the twin Keck telescopes in Hawaii and the European Southern Observatory telescopes in Chile, are exploring the most distant regions of the universe and discovering the first galaxies at large distances. According to the big bang theory, the further the galaxy is, the larger its recession velocity, and the larger the shift towards the red of the spectrum of light from that galaxy. Astronomers thus measure distances in units of red-shift z . The furthest galaxies observed so far are at redshifts of $z \simeq 5$, or 12 billion light-years from the Earth, whose light was emitted when the universe had only about 5 percent of its present age. Only a few galaxies are known at those redshifts, but there are at present various catalogs like the CfA and APM galaxy catalogs, and more recently the IRAS PSCz [See Fig. 2] and Las Campanas redshift surveys, that study the spatial distribution of hundreds of thousands of galaxies up to distances of a billion light-years, or $z < 0.1$, that recede from us at speeds of tens of thousands of kilometres per second. These catalogs are telling us about the evolution of clusters of galaxies in the universe, and already put constraints on the theory of structure formation based on the gravitational collapse of the small inhomogeneities produced during inflation. From these observations one can infer that most galaxies formed at redshifts of order 2 to 4; clusters of galaxies formed at redshifts of order one, and superclusters are forming now. That is, cosmic structure formed from the bottom up, from galaxies to clusters to superclusters, and not the other way around.

Table 1. *The parameters of the standard cosmological model*

(The standard model of cosmology has around 12 different parameters, needed to describe the background spacetime, the matter content and the spectrum of density perturbations. We include here the present range of the most relevant parameters, and the percentage error with which the microwave background probes MAP and Planck (without polarisation) will be able to determine them in the near future. The rate of expansion is written in units of $H = 100 h$ km/s/Mpc)

physical quantity	symbol	present range	MAP	Planck
luminous matter	$\Omega_{\text{lum}} h^2$	0.001 – 0.005	—	—
baryonic matter	$\Omega_{\text{B}} h^2$	0.01 – 0.03	5%	0.6%
cold dark matter	$\Omega_{\text{M}} h^2$	0.2 – 1.0	10%	0.6%
hot dark matter	$\Omega_{\nu} h^2$	0 – 0.3	5%	2%
cosmological constant	$\Omega_{\Lambda} h^2$	0 – 0.8	8%	0.5%
spatial curvature	$\Omega_0 h^2$	0.2 – 1.5	4%	0.7%
rate of expansion	h	0.4 – 0.8	11%	2%
age of the universe	t_0	11 – 17 Gyr	10%	2%
spectral amplitude	Q_{rms}	20 – 30 μK	0.5%	0.1%
spectral tilt	n_{S}	0.5 – 1.5	3%	0.5%
tensor-scalar ratio	r_{ts}	0 – 1.0	25%	10%
reionisation	τ	0.01 – 1.0	20%	15%

This fundamental difference is an indication of the type of matter that gave rise to structure. We know from primordial nucleosynthesis that all the baryons in the universe cannot account for the observed amount of matter, so there must be some extra matter (dark since we don't see it) to account for its gravitational pull. Whether it is relativistic (hot) or non-relativistic (cold) could be inferred from observations: relativistic particles tend to diffuse from one concentration of matter to another, thus transferring energy among them and preventing the growth of structure on small scales. This is excluded by observations, so we conclude that most of the matter responsible for structure formation must be cold. How much there is is a matter of debate at the moment. Some recent analyses suggest that there is not enough cold dark matter to reach the critical density required to make the universe flat. Some other form of energy permeates the universe, if we want to make sense of the present observations. In order to resolve this issue, even deeper galaxy redshift catalogs are underway, looking at millions of galaxies, like the Sloan Digital Sky Survey (SDSS) and the Anglo-Australian two degree field (2dF) Galaxy Redshift Survey, which are at this moment taking data, up to redshifts of $z < 0.5$, or several billion light-years away, over a large region of the sky. These important observations will help astronomers determine the nature of the dark matter and test the validity of the models of structure formation.

However, if galaxies indeed formed from gravitational collapse of density perturbations produced during inflation, one should also expect to see such ripples in the metric as temperature anisotropies in the cosmic microwave background, that is, minute deviations in the temperature of the blackbody spectrum when we look at different directions in the sky. Such anisotropies had been looked for ever since Penzias and Wilson's discovery of the CMB, but had eluded all detection, until NASA's Cosmic Background Explorer (COBE) satellite discovered them in 1992. The reason why it took so long to discover was that they appear as perturbations

in temperature of only one part in 100 000. There is, in fact, a dipolar anisotropy of one part in 1000, in the direction of the Virgo cluster, but that is interpreted consistently as our relative motion with respect to the microwave background due to the local distribution of mass, which attracts us gravitationally towards the Virgo cluster. When subtracted, we are left with a whole spectrum of anisotropies in the higher multipoles (quadrupole, octupole, etc.) [See Fig. 6]. Soon after COBE, other groups quickly confirmed the detection of temperature anisotropies at around $30\mu\text{K}$, at higher multipole numbers or smaller angular scales.

There are at this moment dozens of ground and balloon-borne experiments analysing the anisotropies in the microwave background with angular resolutions from 10 degrees to a few arc-minutes in the sky. The physics of the CMB anisotropies is relatively simple: photons scatter off charged particles (protons and electrons), and carry energy, so they feel the gravitational potential associated with the perturbations imprinted in the metric during inflation. An overdensity of baryons (protons and neutrons) does not collapse under the effect of gravity until it enters the causal Hubble radius. The perturbation continues to grow until radiation pressure opposes gravity and sets up acoustic oscillations in the plasma, very similar to sound waves. Since overdensities of the same size will enter the Hubble radius at the same time, they will oscillate in phase. Moreover, since photons scatter off these baryons, the acoustic oscillations occur also in the photon field and induces a pattern of peaks in the temperature anisotropies in the sky, at different angular scales [See Fig. 7]. The larger the amount of baryons, the higher the peaks. The first peak in the photon distribution corresponds to overdensities that have undergone half an oscillation, that is, a compression, and appear at a scale associated with the size of the horizon at last scattering (when the photons decoupled) or about one degree in the sky. Other peaks occur at harmonics of this, corresponding to smaller angular scales. Since the amplitude and position of the primary and secondary peaks are directly determined by the sound speed (and hence the equation of state) and by the geometry and expansion of the universe, they can be used as a powerful test of the density of baryons and dark matter, and other cosmological parameters.

By looking at these patterns in the anisotropies of the microwave background, cosmologists can determine not only the cosmological parameters, but also the primordial spectrum of density perturbations produced during inflation. It turns out that the observed temperature anisotropies are compatible with a scale-invariant spectrum, as predicted by inflation. This is remarkable, and gives very strong support to the idea that inflation may indeed be responsible for both the CMB anisotropies and the large scale structure of the universe. Different models of inflation have different specific predictions for the fine details associated with the spectrum generated during inflation. It is these minute differences that will allow cosmologists to differentiate among alternative models of inflation and discard those that do not agree with observations. But most importantly, perhaps, is that the pattern of anisotropies predicted by inflation is completely different from those predicted by alternative models of structure formation, like cosmic defects: strings, vortices, textures, etc. These are complicated networks of energy density concentrations left over from an early universe phase transition, analogous to the defects formed in the laboratory in certain kinds of liquid crystals when they go through a phase transition. The cosmological defects have spectral properties very different from those generated by inflation. That is why it is so important to launch

more sensitive, and with better angular resolution, instruments to determine the properties of the CMB anisotropies.

In the first years of the next millenium two new satellites, the Microwave Anisotropy Probe (MAP), to be launched by NASA in the year 2000, and Planck Surveyor, due in 2007, by the European Space Agency, will measure those temperature anisotropies with 100 times better angular resolution and 10 times better sensitivity than COBE, and thus allow cosmologists to determine the parameters of the Standard Cosmological Model with unprecedented accuracy. What makes the microwave background observations particularly powerful is the absence of large systematic errors that plague other cosmological measurements. As we have discussed above, the physics of the microwave background is relatively simple, compared to, say, the physics of supernova explosions, and computations can be done consistently within perturbation theory. Thus most of the systematic errors are theoretical in nature, due to our ignorance about the primordial spectrum of metric perturbations from inflation. There is a great effort at the moment in trying to cover a large region in the parameter space of models of inflation, to ensure that we have considered all possible alternatives, like isocurvature or pressure perturbations, non scale invariant or tilted spectra and non-Gaussian density perturbations.

In particular, inflation also predicts a spectrum of gravitational waves. Their amplitude is directly proportional to the total energy density during inflation, and thus its detection would immediately tell us about the energy scale (and therefore the epoch in the early universe) at which inflation occurred. If the period of inflation responsible for the observed CMB anisotropies is associated with the Gran Unification scale, when the strong and electroweak interactions are supposed to unify, then there is a chance that we might see the effect of gravitational waves in the future satellite measurements, specially from the analysis of photon polarisation in the microwave background maps.

Moreover, the stochastic background of gravitational waves generated during inflation could eventually be observed by the ground-based laser interferometers like LIGO, VIRGO, GEO, TAMA, etc., which will start taking data as gravitational wave observatories in the first years of the next millenium. These are extremely sensitive devices that could distinguish minute spatial variations, of one part in 10^{23} or better, induced when a gravitational wave from a distant source passes through the Earth and distorts the spacetime metric. Gravitational waves moving at the speed of light are a fundamental prediction of general relativity. Their existence was indirectly confirmed by Russell A. Hulse and Joseph H. Taylor, through the precise observations of the decay in the orbital period of the pulsar PSR1913+16, due to the emission of gravitational radiation. In the near future, observations of gravitational waves with laser interferometers will open a completely new window into the universe. It will allow us to observe with a very different probe (that of the gravitational interaction) a huge range of phenomena, from the most violent processes in our galaxy and beyond, like supernova explosions, neutron star collisions, quasars, gamma ray bursts, etc., to the origin of the universe.

In our quest for the parameters of the standard cosmological model, various groups are searching for distant astrophysical objects that can serve as standard candles to determine the distance to the object from their observed apparent luminosity. A candidate that has recently been exploited with great success is a certain type of supernova explosions at large redshifts. These are stars at the end of their

life cycle that become unstable and violently explode in a natural thermonuclear explosion that out-shines their progenitor galaxy. The intensity of the distant flash varies in time, it takes about three weeks to reach its maximum brightness and then it declines over a period of months. Although the maximum luminosity varies from one supernova to another, depending on their original mass, their environment, etc., there is a pattern: brighter explosions last longer than fainter ones. By studying the light curves of a reasonably large statistical sample, cosmologists from two competing groups, the Supernova Cosmology Project and the High-z Supernova Project, are confident that they can use this type of supernovae as standard candles. Since the light coming from some of these rare explosions has travelled for a large fraction of the size of the universe, one expects to be able to infer from their distribution the spatial curvature and the rate of expansion of the universe [See Fig. 8]. One of the surprises that these observations have revealed is that the universe appears to be accelerating, instead of decelerating as was expected from the general attraction of matter; something seems to be acting as a repulsive force on very large scales. The most natural explanation for this is the existence of a cosmological constant, a diffuse vacuum energy that permeates all space and, as explained above, gives the universe an acceleration that tends to separate gravitationally bound systems from each other. The origin of such a vacuum energy is one of the biggest problems of modern physics. Its observed value is 120 orders of magnitude smaller than predicted by fundamental high energy physics. If confirmed, it will pose a real challenge to theoretical physics, one that may affect its most basic foundations. However, it is still premature to conclude that this is indeed the case, because of possibly large systematic errors inherent to most cosmological measurements, given our impossibility to do experiments under similar circumstances in the laboratory.

3. The origin of matter in the universe

Cosmological inflation may be responsible for the metric perturbations that later gave rise to the large scale structures we see in the universe, but where did all the matter in the universe come from? why isn't all in photons which would have inevitably redshifted away in a cold universe devoid of life? How did we end up being matter dominated? Everything we see in the universe, from planets and stars, to galaxies and clusters of galaxies, is made out of matter, so where did the antimatter in the universe go? Is this the result of an accident, a happy chance occurrence during the evolution of the universe, or is it an inevitable consequence of some asymmetry in the laws of nature? Theorists believe that the excess of matter over antimatter comes from fundamental differences in their interactions soon after the end of inflation.

Inflation is an extremely efficient mechanism in diluting any particle species or fluctuations. At the end of inflation, the universe is empty and extremely cold, dominated by the homogeneous coherent mode of the inflaton. Its potential energy density is converted into particles, as the inflaton field oscillates coherently around the minimum of its potential [See Fig. 3]. These particles are initially very far from equilibrium, but they strongly interact among themselves and soon reach thermal equilibrium at a very large temperature. From there on, the universe expanded isoentropically, cooling down as it expanded, in the way described by the standard

Table 2. *The standard model of particle physics*

(The primary constituents of matter, quarks and leptons, are divided into three generations. The first generation contains the up and down quarks and antiquarks, as well as the electron, its neutrino and their antiparticles. Ordinary matter is made out almost exclusively of particles of the first generation: an atom's nucleus contains protons and neutrons, themselves made of up and down quarks. The other generations, equally abundant in the early universe, may still exist in hot environments such as neutron star cores, and are routinely produced in accelerators.)

Transmitters of force				
Weak bosons		Photon	Gluon	Higgs
W^\pm	Z^0	γ	g	H^0
Constituents of matter				
Particle		Symbol	Charge	Mass (GeV/ c^2)
First generation				
up	u	+2/3	0.03	quarks
down	d	-1/3	0.06	
electron	e	-1	0.0005	leptons
electron neutrino	ν_e	0	0?	
Second generation				
charm	c	+2/3	1.3	quarks
strange	s	-1/3	0.14	
muon	μ	-1	0.106	leptons
muon neutrino	ν_μ	0	0?	
Third generation				
top	t	+2/3	174	quarks
bottom	b	-1/3	4.3	
tau	τ	-1	1.7	leptons
tau neutrino	ν_τ	0	0?	

hot big bang model. Thus the origin of the big bang itself, and the matter and energy we observe in the universe today, can be traced back to the epoch in which the inflaton energy density decayed into particles. Such a process is called reheating of the universe.

Recent developments in the theory of reheating suggest that the decay of the inflaton energy could be explosive, due to the coherent oscillations of the inflaton, which induces its stimulated decay. The result is a resonant production of particles in just a few inflaton oscillations, an effect very similar to the stimulated emission of a laser beam of photons. The number of particles produced this way is exponentially large, which may explain the extraordinarily large entropy, of order 10^{89} particles, in our observable patch of the universe today. However, the inflaton is supposed to be a neutral scalar field, and thus its interactions cannot differentiate between particles and antiparticles. How did we end up with more matter than antimatter? The study of this cosmological asymmetry goes by the name of baryogenesis since baryons (mainly protons and neutrons) are the fundamental constituents of matter in planets, stars and galaxies in the universe today. So, what are the conditions for baryogenesis?

Everything we know about the properties of elementary particles is included in the standard model of particle physics. It describes more than a hundred observed

particles and their interactions in terms of a few fundamental constituents: six quarks and six leptons, and their antiparticles [See Table 2]. The standard model describes three types of interactions: the electromagnetic force, the strong and the weak nuclear forces. These forces are transmitted by the corresponding particles: the photon, the gluon and the W and Z bosons. The theory also requires a scalar particle, the Higgs particle, responsible for the masses of quarks and leptons and the breaking of the electroweak symmetry at an energy scale 100 times the mass of the proton. The Higgs is believed to lie behind most of the mysteries of the standard model, including the asymmetry between matter and antimatter.

Symmetries are fundamental properties of any physical theory. A theory is symmetric under certain symmetry operation, like reflection, if its laws apply equally well after such an operation is performed on part of the physical system. An important example is the operation called parity reversal, denoted by P. It produces a mirror reflection of an object and rotates it 180 degrees about an axis perpendicular to the mirror. A theory has P symmetry if the laws of physics are the same in the real and the parity-reversed world. Particles such as leptons and quarks can be classified as right- or left-handed depending on the sense of their internal rotation, or spin, around their direction of motion. If P symmetry holds, right-handed particles behave exactly like left-handed ones. The laws of electrodynamics and the strong interactions are the same in a parity-reflected universe. But, as Chien-Shiung Wu discovered in 1957, the weak interaction acts very differently on particles with different handedness: only left-handed particles can decay by means of the weak interaction, not right-handed ones. Moreover, as far as we know, there are no right-handed neutrinos, only left-handed. So the weak force violates P.

Another basic symmetry of nature is charge conjugation, denoted by C. This operation changes the quantum numbers of every particle into those of its antiparticle. Charge symmetry is also violated by the weak interactions: antineutrinos are not left-handed, only right-handed. Combining C and P one gets the charge-parity symmetry CP, which turns all particles into their antiparticles and also reverses their handedness: left-handed neutrinos become right-handed antineutrinos [See Fig. 9]. Although charge and parity symmetry are individually broken by the weak interaction, one expects their combination to be conserved. However, in 1964, a groundbreaking experiment by James Cronin, Val Finch and René Turlay at Brookhaven National Laboratory showed that CP was in fact violated to one part in 1000. It was hard to see why CP symmetry should be broken at all and even more difficult to understand why the breaking was so small. Soon after, in 1972, Makoto Kobayashi and Toshihide Maskawa showed that CP could be violated within the standard model if three or more generations of quarks existed, because of CP nonconserving phases that could not be rotated away. Only two generations were known at the time, but in 1975 Martin L. Perl and collaborators discovered the tau lepton at the Stanford Linear Accelerator Centre (SLAC), the first ingredient of the third generation. Only recently the last quark in the family was discovered at Fermilab, the top quark.

But how does this picture fit in the evolution of the universe? In 1967, the Russian physicist Andrei Sakharov pointed out the three necessary conditions for the baryon asymmetry of the universe to develop. First, we need interactions that do not conserve baryon number B, otherwise no asymmetry could be produced in the first place. Second, C and CP symmetry must be violated, in order to differentiate

between matter and antimatter, otherwise B nonconserving interactions would produce baryons and antibaryons at the same rate, thus maintaining zero net baryon number. Third, these processes should occur out of thermal equilibrium, otherwise particles and antiparticles, which have the same mass, would have equal occupation numbers and would be produced at the same rate. The standard model is baryon symmetric at the classical level, but violates B at the quantum level, through the chiral anomaly. Electroweak interactions violate C and CP, but the magnitude of the latter is clearly insufficient to account for the observed baryon asymmetry. This failure suggests that there must be other sources of CP violation in nature, and thus the standard model of particle physics is probably incomplete.

One of the most popular extensions of the standard model includes a new symmetry called supersymmetry, which relates bosons (particles that mediate interactions) with fermions (the constituents of matter). Those extensions generically predict other sources of CP violation coming from new interactions at scales above 1000 times the mass of the proton. Such scales will soon be explored in the first years of the next millenium by particle colliders like the Large Hadron Collider (LHC) at CERN, the European Centre for Particle Physics, and by the Tevatron at Fermilab. The mechanism for baryon production in the early universe in these models relies on the strength of the electroweak phase transition, as the universe cooled and the symmetry was broken. Only for strongly first order phase transitions is the universe sufficiently far from equilibrium to produce enough baryon asymmetry. Unfortunately, the phase transition in these models is invariably too weak to account for the observed asymmetry, so some other mechanism is needed.

If reheating after inflation occurred in an explosive way, via the resonant production of particles from the inflaton decay, as recent developments suggest, then the universe has actually gone through a very non-linear, non-perturbative and very far from equilibrium stage, before thermalising via particle interactions. Electroweak baryogenesis could then take place during that epoch, soon after the end of low energy inflation at the electroweak scale. Such models can be constructed but require a specially flat direction (a very small mass for the inflaton) during inflation, in order to satisfy the constraints from the amplitude of temperature anisotropies seen by COBE. Such flat directions are generic in supersymmetric extensions of the standard model. After inflation, the inflaton acquires a large mass from its interaction with the Higgs field.

The crucial ingredient of departure from equilibrium, necessary for the excess production of baryons over antibaryons, is strongly present in this new scenario of baryogenesis, as the universe develops from a zero temperature and zero entropy state, at the end of inflation, to a thermal state with exponentially large numbers of particles, the origin of the standard hot big bang. If, during this stage, fundamental or effective interactions that are B, C and CP violating were fast enough compared to the rate of expansion, the universe could have ended with the observed baryon asymmetry of one part in 10^{10} , or one baryon per 10^9 photons today, as deduced from observations of the light element abundances [See Fig. 1]. Recent calculations suggest that indeed, the required asymmetry could be produced as long as some new physics, just above the electroweak symmetry breaking scale, induces a new effective CP violating interaction.

These new phenomena necessarily involve an interaction between the Higgs particle, responsible for the electroweak symmetry breaking, and the inflaton field,

responsible for the period of cosmological inflation. Therefore, for this scenario to work, it is expected that both the Higgs and the inflaton particles be discovered at the future particle physics colliders like the LHC and the Next Linear Collider (NLC), to be built in the next millenium. Furthermore, this new physics would necessarily involve new interactions in the quark sector, for example inducing CP violations in the B meson (a bound state composed of a bottom quark and an antidown quark) system. Such violations are the main research objective of the B factory at SLAC in California and at KEK, the High Energy Accelerator Research Organisation in Tsukuba, Japan. Those experiments will be taking data in a few months time, at the turn of the millenium, and could give us clues on the issues of the matter-antimatter asymmetry and thus on baryogenesis from reheating after inflation.

If confirmed, such a new scenario of baryogenesis would represent a leap forward in our understanding of the universe from the unifying paradigm of inflationary cosmology. Furthermore, it would bring inflation down to a scale where present or future particle physics experiments would be able to explore it quite thoroughly. Cosmological inflation thus enters the realm of testable low energy particle physics.

4. Conclusions

We have entered a new era in cosmology, were a host of high precision measurements are already posing challenges to our understanding of the universe: the density of ordinary matter and the total amount of energy in the universe; the microwave background anisotropies on a fine scale resolution; primordial deuterium abundance from quasar absorption lines; the acceleration parameter of the universe from high-redshift supernovae observations; the rate of expansion from gravitational lensing; large scale structure measurements of the distribution of galaxies and their evolution, and many more, which already put constraints on the parameter space of cosmological models [See Fig. 10]. However, these are only the forerunners of the precision era in cosmology that will dominate the new millenium, and will make cosmology a phenomenological science.

It is important to bear in mind that all physical theories are approximations of reality that can fail if pushed too far. Physical science advances by incorporating earlier theories that are experimentally supported into larger, more encompassing frameworks. The standard big bang theory is supported by a wealth of evidence, nobody really doubts its validity anymore. However, in the last decade it has been incorporated into the larger picture of cosmological inflation, which has become the new standard cosmological model. All cosmological issues are now formulated in the context of the inflationary cosmology. It is the best explanation we have at the moment for the increasing set of cosmological observations.

In the next few years we will have an even larger set of high-quality observations that will test inflation and the cold dark matter paradigm of structure formation, and determine most of the 12 or more parameters of the standard cosmological model to a few percent accuracy [See Table. 1]. It may seem that with such a large number of parameters one can fit almost anything. However, that is not the case when there is enough quantity and quality of data. An illustrative example is the standard model of particle physics, with around 21 parameters and a host of precise measurements from particle accelerators all over the world. This model is

nowadays rigorously tested, and its parameters measured to a precision of better than a percent in some cases. It is clear that high precision measurements will make the standard model of cosmology as robust as that of particle physics. In fact, it has been the technological advances of particle physics detectors that are mainly responsible for the burst of new data coming from cosmological observations. This is definitely a very healthy field, but there is still a lot to do. With the advent of better and larger precision experiments, cosmology is becoming a mature science, where speculation has given way to phenomenology.

There are still many unanswered fundamental questions in this emerging picture of cosmology. For instance, we still do not know the nature of the inflaton field, is it some new fundamental scalar field in the electroweak symmetry breaking sector, or is it just some effective description of a more fundamental high energy interaction? Hopefully, in the near future, experiments in particle physics might give us a clue to its nature. Inflation had its original inspiration in the Higgs field, the scalar field supposed to be responsible for the masses of elementary particles (quarks and leptons) and the breaking of the electroweak symmetry. Such a field has not been found yet, and its discovery at the future particle colliders would help understand one of the truly fundamental problems in physics, the origin of masses. If the experiments discover something completely new and unexpected, it would automatically affect inflation at a fundamental level.

One of the most difficult challenges that the new cosmology will have to face is understanding the origin of the cosmological constant, if indeed it is confirmed by independent sets of observations. Ever since Einstein introduced it as a way to counteract gravitational attraction, it has haunted cosmologists and particle physicists for decades. We still do not have a mechanism to explain its extraordinarily small value, 120 orders of magnitude below what is predicted by quantum physics. For several decades there has been the reasonable speculation that this fundamental problem may be related to the quantisation of gravity. General relativity is a classical theory of spacetime, and it has proved particularly difficult to construct a consistent quantum theory of gravity, since it involves fundamental issues like causality and the nature of spacetime itself.

The value of the cosmological constant predicted by quantum physics is related to our lack of understanding of gravity at the microscopic level. However, its effect is dominant at the very largest scales of clusters or superclusters of galaxies, on truly macroscopic scales. This hints at what is known in quantum theory as an anomaly, a quantum phenomenon relating both ultraviolet (microscopic) and infrared (macroscopic) divergences. We can speculate that perhaps general relativity is not the correct description of gravity on the very largest scales. In fact, it has been only in the last few billion years that the observable universe has become large enough that these global effects could be noticeable. In its infancy, the universe was much smaller than it is now, and presumably general relativity gave a correct description of its evolution, as confirmed by the successes of the standard big bang theory. As it expanded, larger and larger regions were encompassed and therefore deviations from general relativity would slowly become important. It may well be that the recent determination of a cosmological constant from observations of supernovae at high redshifts is hinting at a fundamental misunderstanding of gravity on the very large scales.

If this were indeed the case, we should expect that the new generation of precise

cosmological observations will not only affect our cosmological model of the universe but also a more fundamental description of nature.

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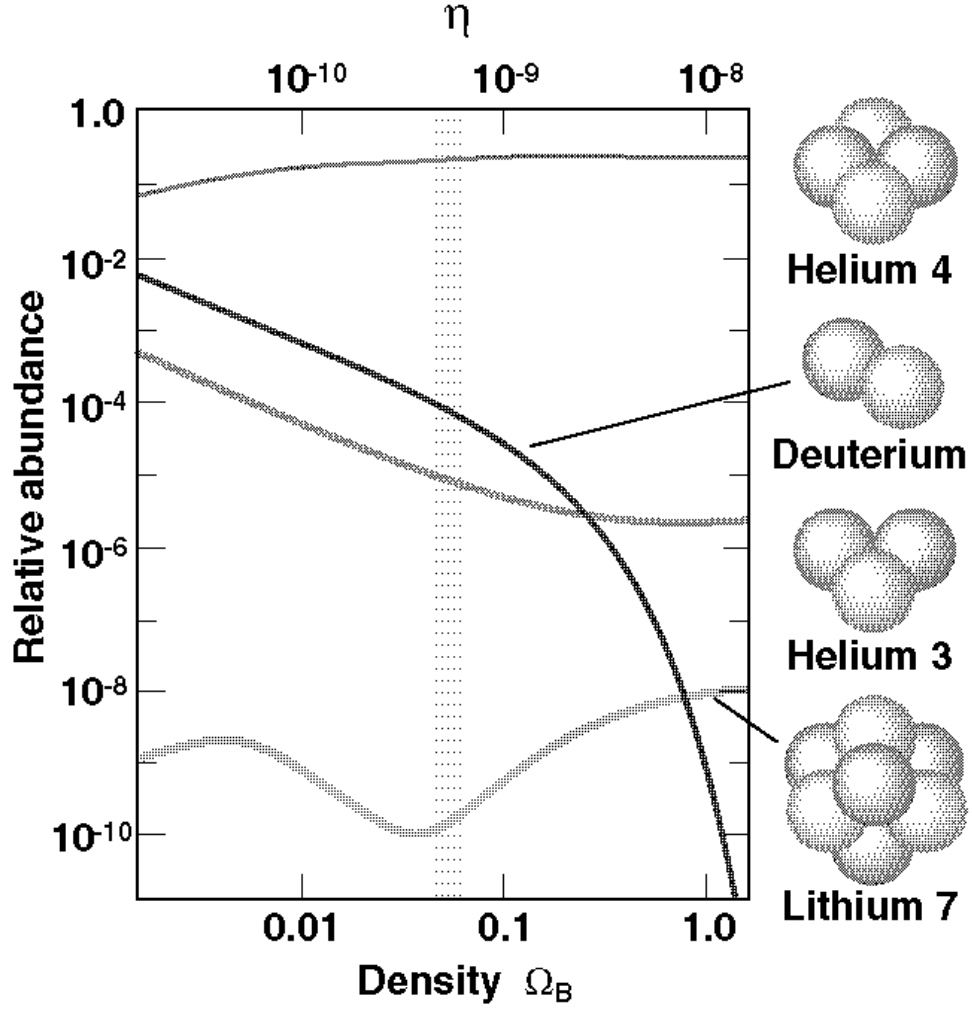


Figure 1. The density of baryons (neutrons and protons) in the universe determines the relative abundances of the lighter elements, hydrogen, helium and lithium. For a higher density universe, the computed helium abundance is little different, but the computed abundance of deuterium is considerably lower. Thus observations of primordial deuterium place very strong bounds on the present density of baryons. The shaded region is consistent with the observations, ranging over 10 orders of magnitude, from 24 percent for helium to one part in 10^{10} for lithium. This impressive quantitative agreement is one of the main successes of the standard big bang cosmology. The observed baryon density Ω_B corresponds to a baryon to photon ratio η of one part in 10^9 .
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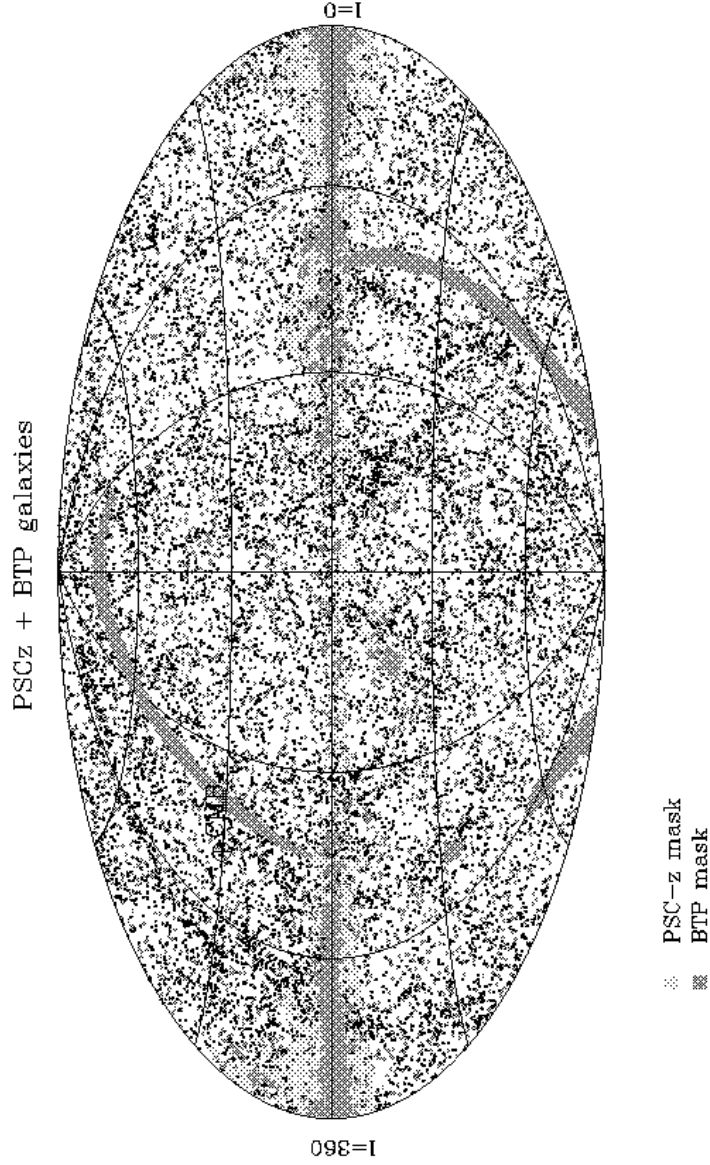


Figure 2. The IRAS Point Source Catalog redshift survey contains some 15 000 galaxies, covering over 83 percent of the sky up to redshifts $z \leq 0.05$. We show here the projection of the galaxy distribution in galactic coordinates. The filled-in regions indicate unobserved or obscured regions, specially along the horizontal strip surrounding the galactic plane. Future galaxy surveys like the Sloan Digital Sky Survey will map a million galaxies up to redshifts $z \leq 0.5$.

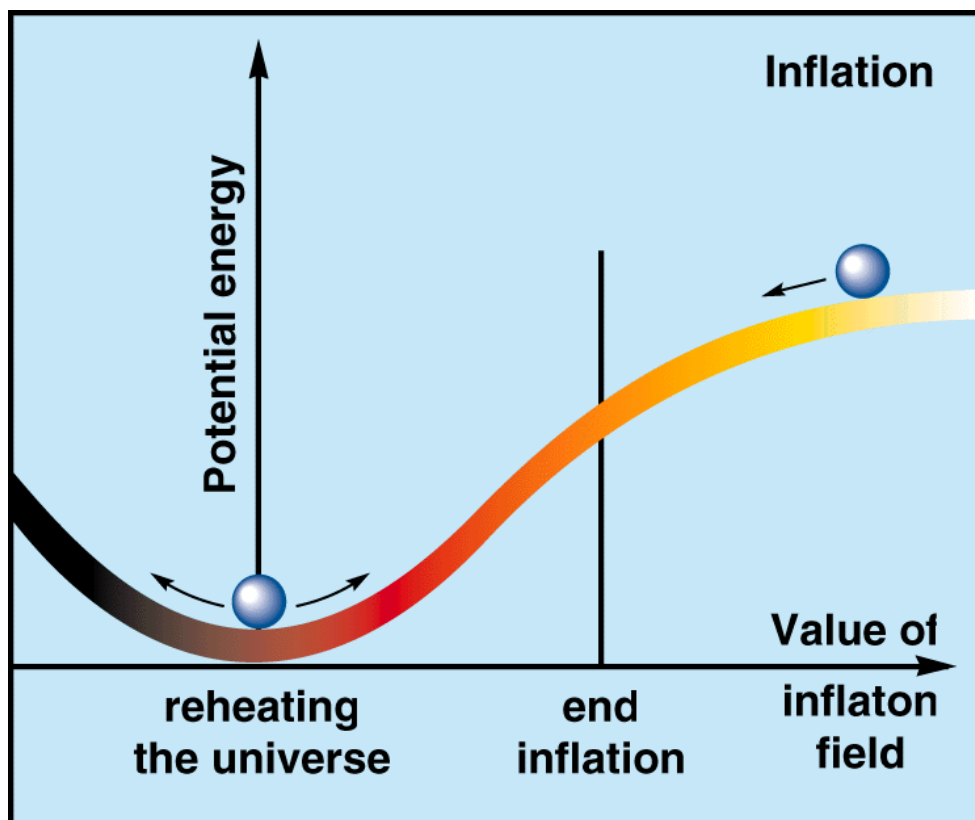


Figure 3. The inflaton field can be represented as a ball rolling down a hill. During inflation the energy density is approximately constant, driving the tremendous expansion of the universe. When the ball starts to oscillate around the bottom of the hill, inflation ends and the inflaton energy decays into particles. In certain cases, the coherent oscillations of the inflaton could generate a resonant production of particles which soon thermalise, reheating the universe.

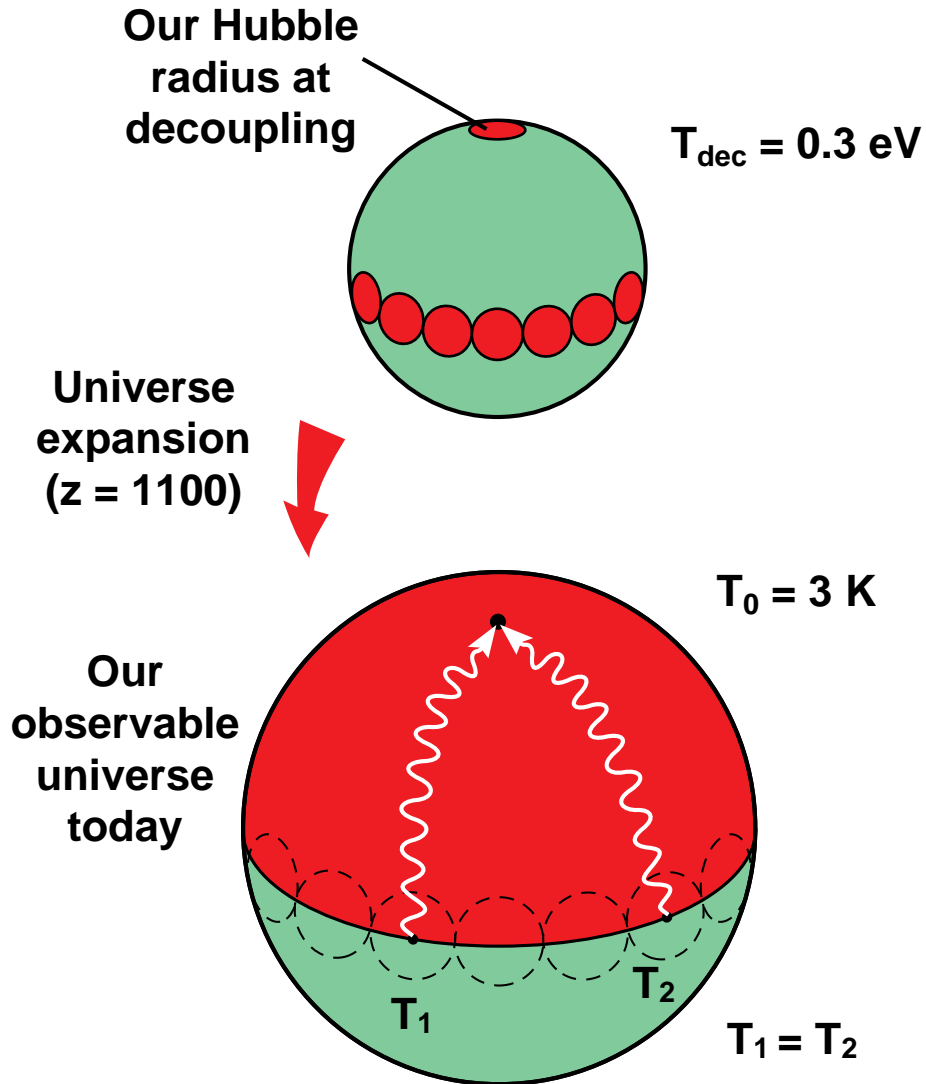


Figure 4. Perhaps the most acute problem of the big bang model is explaining the extraordinary homogeneity and isotropy of the microwave background. Information cannot travel faster than the speed of light, so the causal region (so-called horizon or Hubble radius) at the time of photon decoupling could not be larger than 300 000 light-years across, or about one degree projected in the sky today. So why regions that are separated by more than a degree in the sky should have the same temperature, when the photons that come from those two distant regions could not have been in causal contact when they were emitted. This constitutes the so-called horizon problem, which is spectacularly solved by inflation.

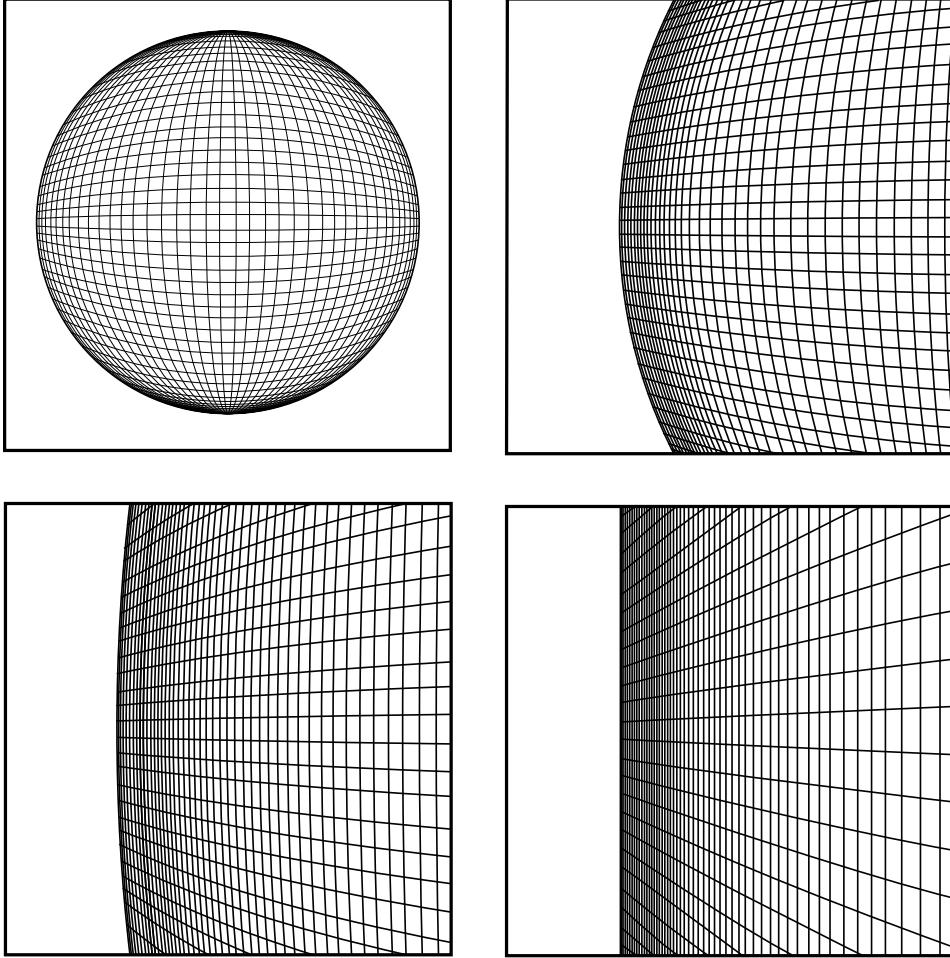


Figure 5. The exponential expansion during inflation made the radius of curvature of the universe so large that our observable patch of the universe today appears essentially flat, analogous (in three dimensions) to how the surface of a balloon appears flatter and flatter as we inflate it to enormous sizes. This is a crucial prediction of cosmological inflation that will be tested to extraordinary accuracy in the next few years.

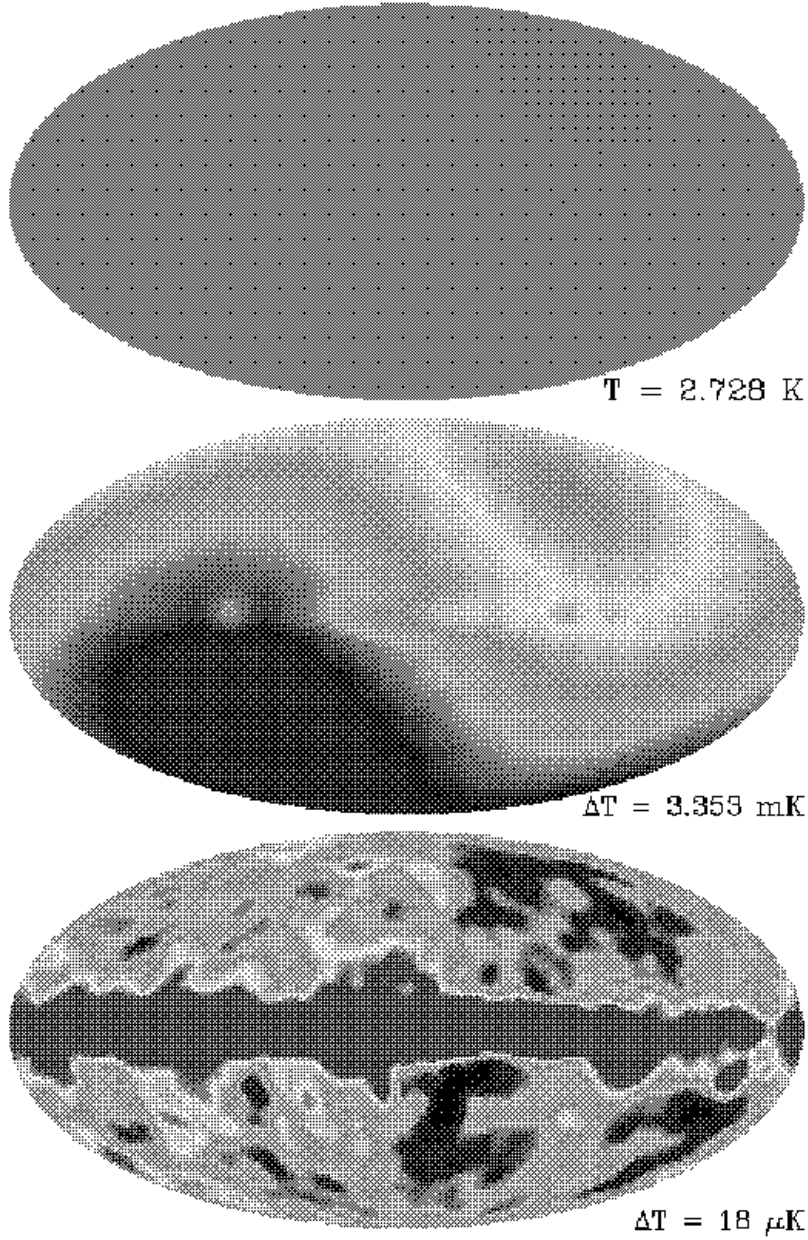


Figure 6. The microwave background sky as seen by COBE. The upper panel shows the extraordinary homogeneity and isotropy of the universe: the microwave background has a uniform blackbody temperature of $T = 2.728 \text{ K}$. The middle panel shows the dipole, corresponding to our relative motion with respect to the microwave background in the direction of the Virgo cluster. The lower panel shows the intrinsic CMB anisotropies, corresponding to the quadrupole and higher multipoles, at the level of one part in 10^5 . The horizontal bar (red) corresponds to the microwave emission of our galaxy, which should be subtracted.

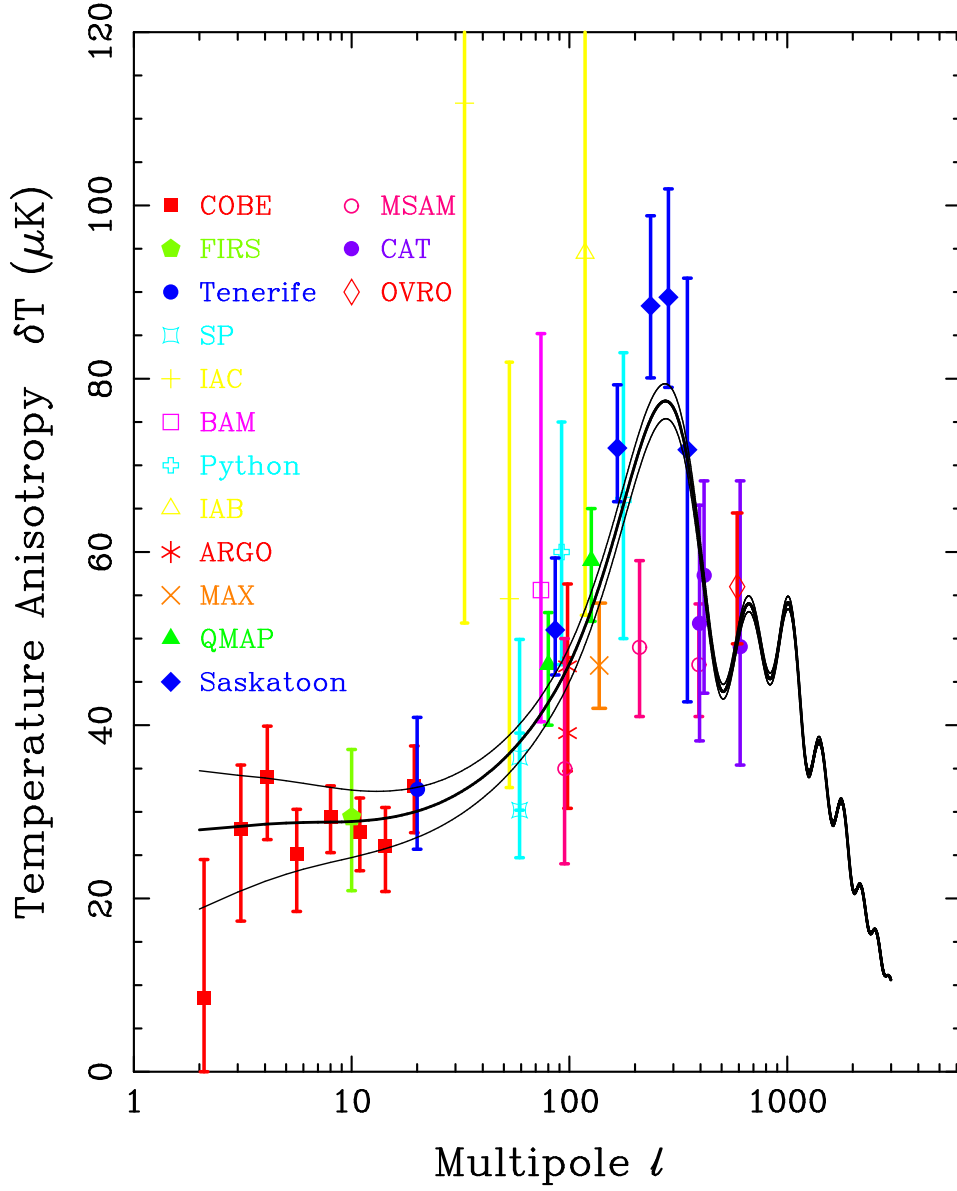


Figure 7. There are at present dozens of ground and balloon-borne experiments looking at the microwave background temperature anisotropies with angular resolutions from 10 degrees to a few arc-minutes in the sky, corresponding to multipole numbers $l = 2 - 3000$. Present observations suggest the existence of a peak in the angular distribution, as predicted by inflation. The theoretical curve (thick line) illustrates a particular model which fits the data, together with the (cosmic variance) uncertainty with which the future satellites MAP and Planck will be able to measure the microwave background anisotropies.

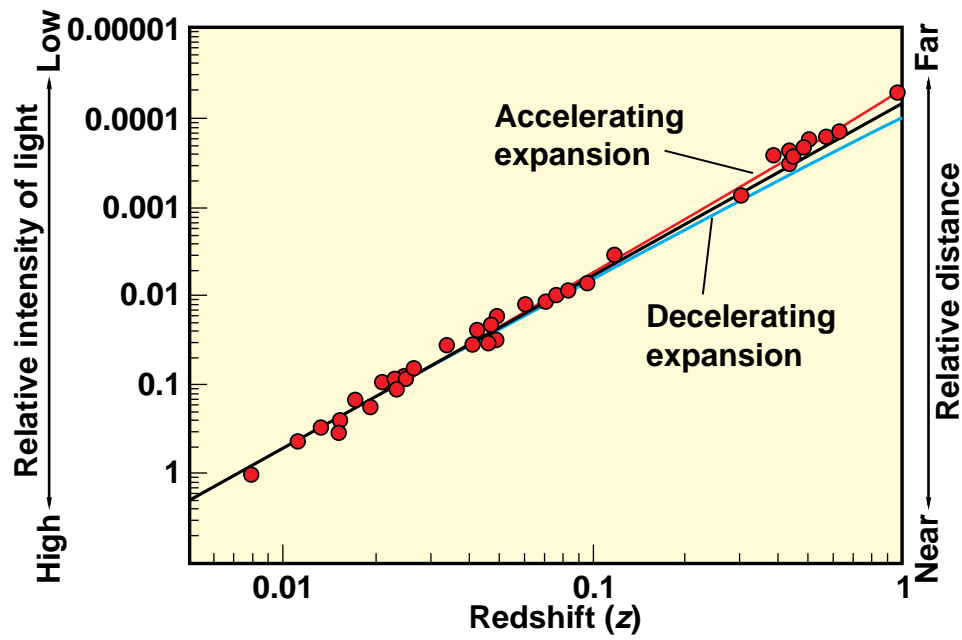


Figure 8. The Hubble diagram for high redshift supernovae (red dots). Observations deviate slightly but significantly from the Einstein-de Sitter model (blue line), a flat universe with no cosmological constant, which would be decelerating due to the attraction of matter. These observations indicate that there is only 30 percent of the matter necessary to make it flat (black line), and therefore decelerates more slowly than predicted. The measurements even suggest that the universe is accelerating (red line), as if due to a nonzero cosmological constant.

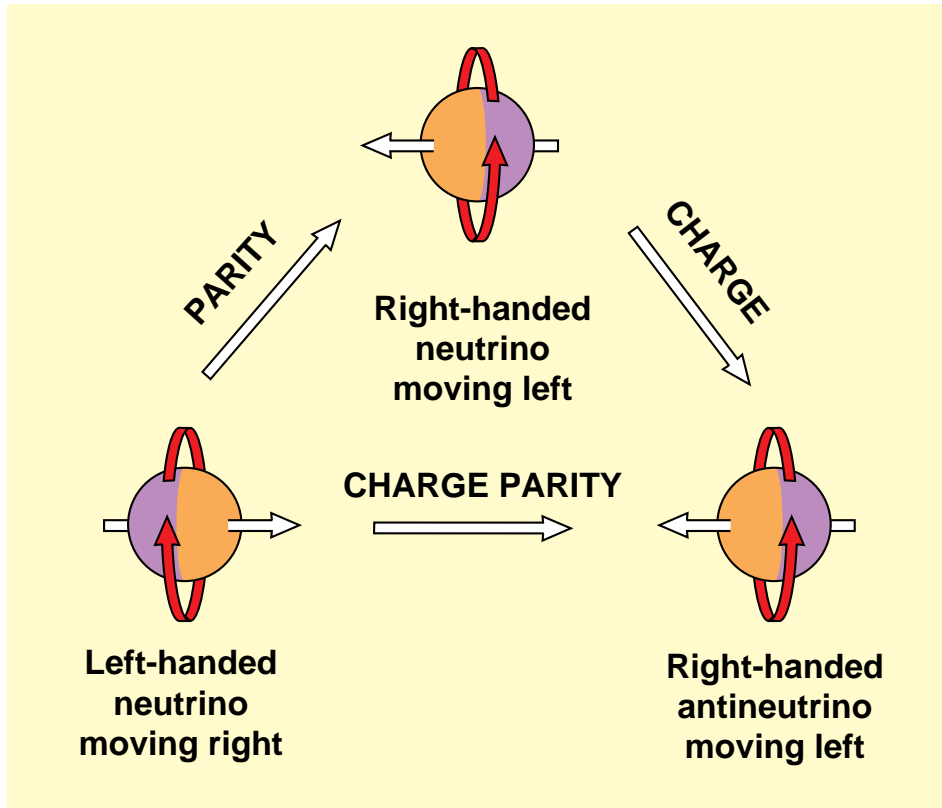


Figure 9. Symmetries are vital to the study of physics, and few are more intriguing than the combination of charge and parity. Charge reversal gives the opposite sign to all quantum numbers such as electric charge, changing a particle into its antiparticle. Parity reversal reflects an object and also rotates it by 180 degrees. The laws of classical mechanics and electromagnetism, as well as the strong interactions that maintain quarks and nucleons together, are invariant under either of these symmetry operations. The weak interactions, however, are changed by both charge and parity reversal. For many years it appeared that the combination charge-parity together was invariant even for weak interactions. However, experiments in 1964 shattered this illusion, posing the puzzle of why nature looks different when reflected in the charge-parity mirror. It may have an answer in the origin of the matter-antimatter asymmetry.

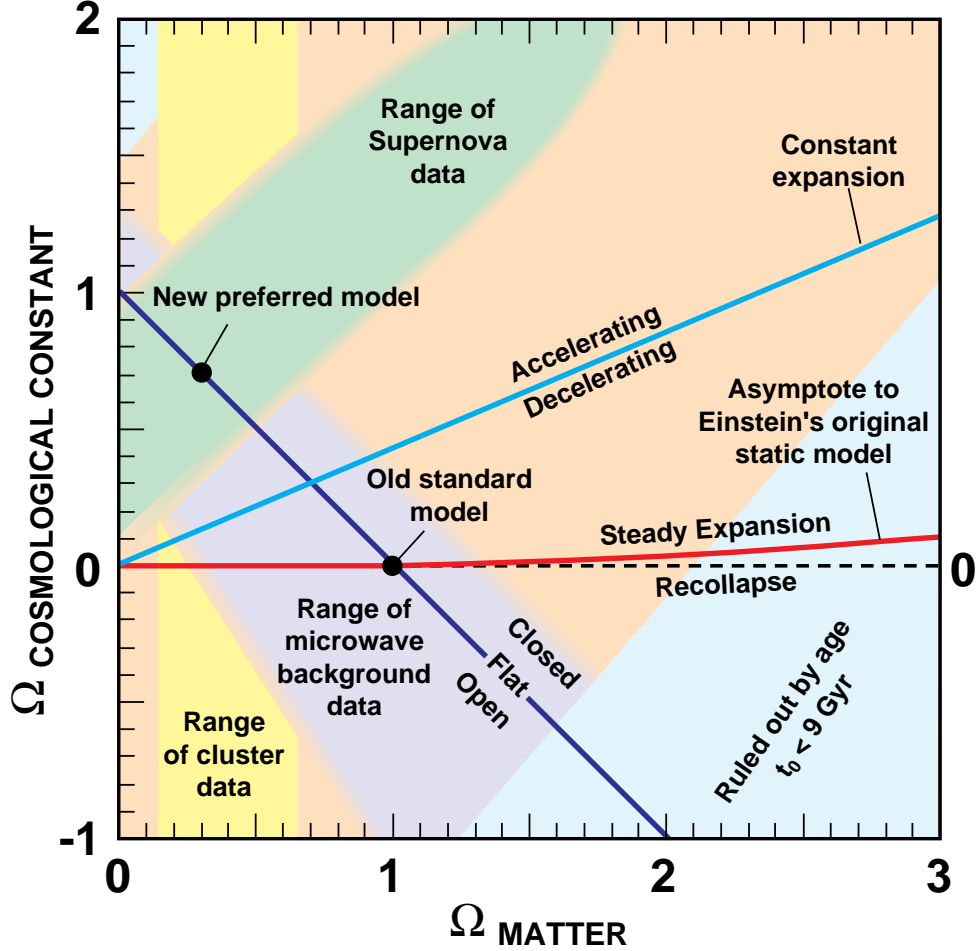
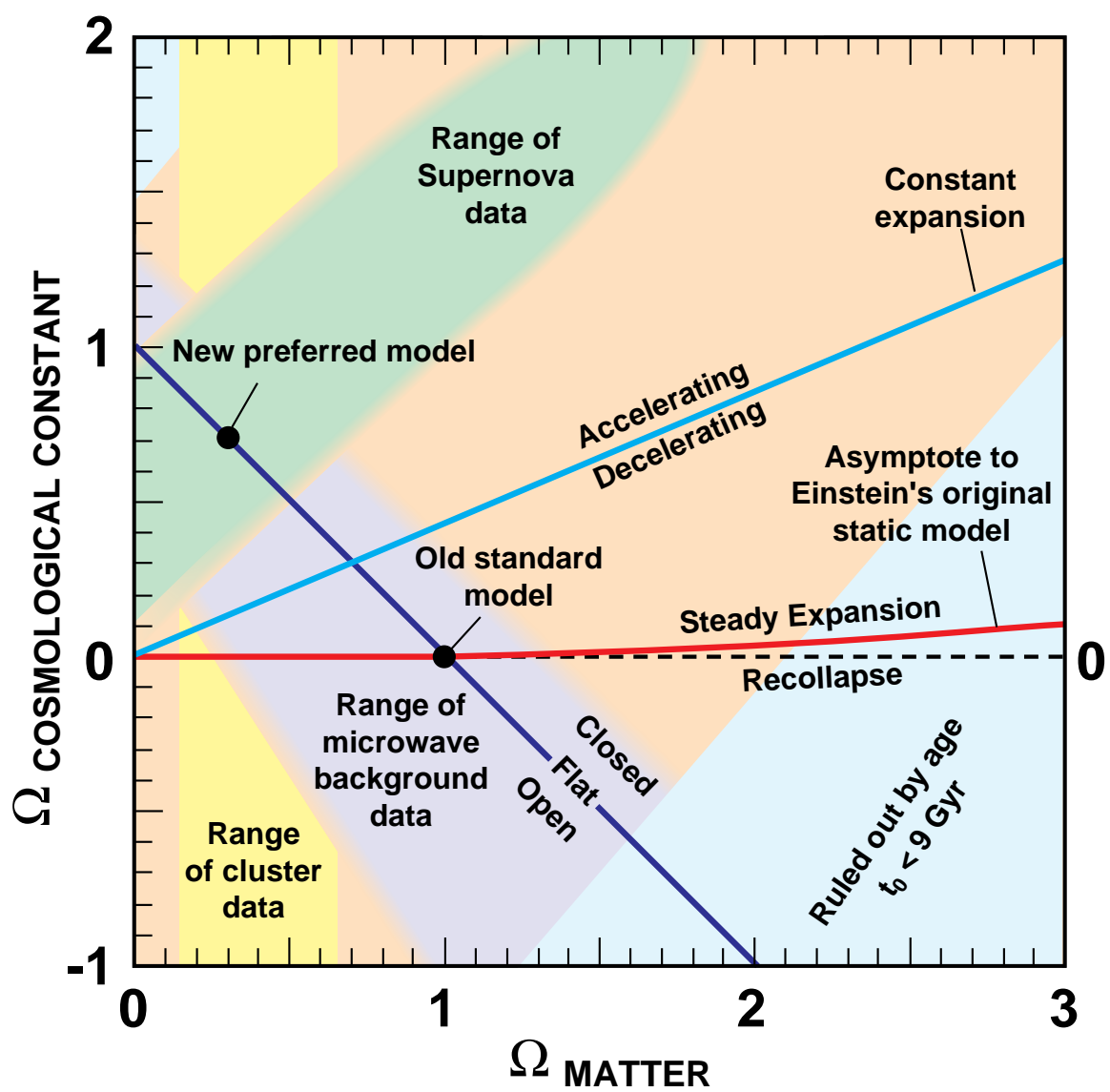
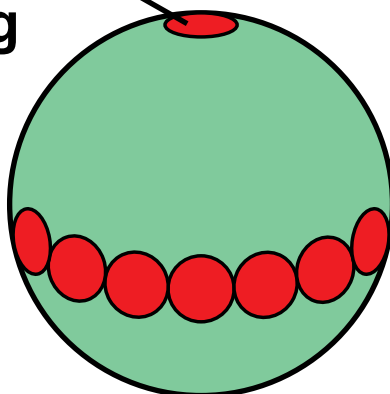


Figure 10. The evolution of the universe depends on two crucial parameters: the average density of matter (horizontal axis) and the energy density in the cosmological constant (vertical axis). Their values produce three very different effects. First, their sum gives the total cosmic energy content and determines the geometry of spacetime (violet line). Second, their difference characterises the relative strength of expansion and gravity, and determines how the expansion rate changes with time (blue line). These two effects have been probed by recent observations (green yellow and purple regions). The third, a balance between the two densities, determines the fate of the universe (red line). The three effects have many different combinations. Surprisingly enough, at present, all observations seem to lie within a narrow region of parameter space.



Our Hubble
radius at
decoupling

$$T_{\text{dec}} = 0.3 \text{ eV}$$

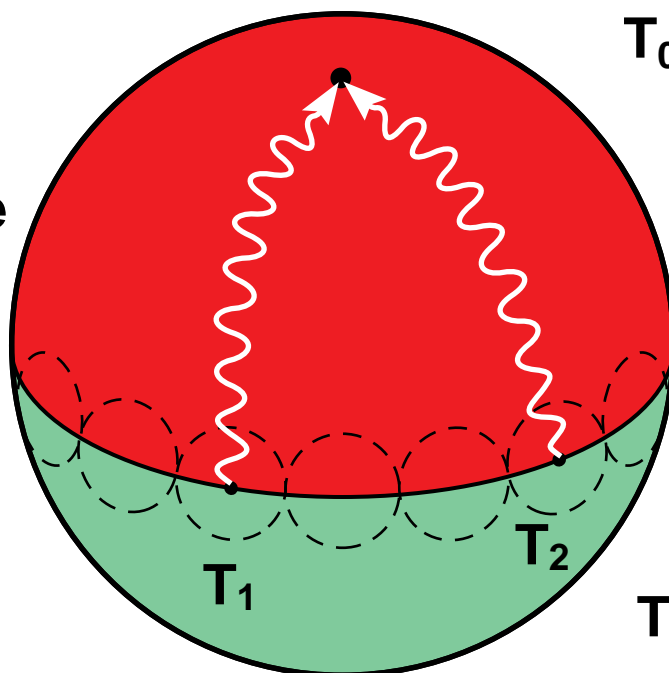


Universe
expansion
($z = 1100$)



Our
observable
universe
today

$$T_0 = 3 \text{ K}$$



$$T_1 = T_2$$

